DSN Model for Use In Strategic Planning

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A System Dynamics Model of the DSN is being developed to support strategic planning for the Network. Applications for the model are described, as well as the foundations of System Dynamics and the methodology being used to develop the model. Activities to date and plans for future work are also discussed.

I. Introduction

In the course of planning, some of the more difficult questions for managers to address are of the following kind:

What behavior patterns does our system exhibit, and what causes them?

What effect would a new policy have on the behavior of our system?

What policy, decision, or action will create a given desired change in our system's behavior?

What would be the effect on our system of a major outside event?

These are strategic questions — questions that address "should" more than "how" and that appear throughout the process of long-range planning. Such questions, and the difficulties involved in answering them, prompted the formation of the TDA Network Dynamic Model task.

This task provides for the development, testing, and validation of one or more models of the Deep Space Network system. These DSN Models (DM) will be designed to support TDA managers in strategic planning for the Mark IV and Mark V eras (i.e., planning for the next 20 years). The modeling technique chosen for DM is System Dynamics; its strength lies in the ability to model the *structure* of a complex system, thus enabling a manager to better understand the forces producing the system behavior and effect desired changes thereto.

The intent of this article is to describe the System Dynamics technique and its application to the DSN. Section II discusses the foundations of System Dynamics and Section III the methodology that will be used to produce, test, and validate the DSN Model. A summary of progress to date and a discussion of future work are given in Sections IV and V.

II. Fundamentals of System Dynamics

The System Dynamics technique is a tool for policy design and analysis in the environment of a complex system. Although a relatively new discipline, System Dynamics has been successfully applied to the strategic planning process in various major corporations and R&D organizations.

System Dynamics was developed at M.I.T. under the direction of J. Forrester. Its foundations lie in the study of feedback system behavior in physical systems; this approach was then extended to the analysis of social systems. In System Dynamics, cybernetic theory is combined with perceptions of the system structure, derived primarily from managerial experience. Using computer simulation, a model of system structure is developed in which policy can be designed, and the consequences of that policy evaluated.

A. Characteristics of Complex Systems

The DSN is representative of a large, complex system. One approach to solving problems in such a system is to institute a new policy and try it out "in vivo." Among the difficulties associated with this approach are: (1) the policy may not work and the system is left in worse condition than before the intervention, (2) if the policy is effective, it may not be possible to determine why, and (3) it may be very difficult to assess how the same policy might work under changed conditions or in other parts of the system (Ref. 1).

Instead of testing policies in the real system, it is possible to use System Dynamics to model the dynamic, or time varying behavior of complex systems. The interrelationships between policies and system state are analyzed, and high and low leverage policies identified.

There are some very compelling reasons to try out new policies "in vitro," i.e., in a simulation environment. These reasons are based upon the behavioral characteristics of complex systems:

(1) The nature of complex systems renders them resistant to most policy changes. Only 5 to 10% of the attempted changes are effective, as much as 50% of the changes are detrimental, and the rest have no effect (Ref. 2).

(2) Complex systems exhibit counterintuitive behavior. The manifestation of a symptom may be far removed in time and space from its cause. Unrelated conditions resulting from the dynamics of the system structure may have an apparent cause and effect relationship due to their juxtaposition in time and location (Ref. 3).

(3) Complex systems can be controlled through leverage points: while they are quite insensitive to changes in most of their parameters, it is possible to identify points where a small policy change can produce a large change throughout a system. There are relatively few such high leverage points, and they frequently are in unexpected places (Ref. 3).

(4) The short-term response to change in a complex system frequently occurs in the opposite direction to the long-term outcome (Ref. 3). This necessitates policy

tradeoffs such as whether to implement an improvement in the present at the expense of the future.

(5) External assistance applied to the system may be internally counteracted (Ref. 3). The burden of system improvement is transferred to the intervening agent because the assistance in effect becomes part of the system.

(6) Complex systems can appear to exhibit lower performance than expected. This is due to the detrimental effects of design changes suggested by the counterintuitive nature of the system, and by the opposing directions of short- and long-term responses to change (Ref. 3).

Complex systems do not lend themselves to traditional linear mathematical modeling techniques. As implied above, these systems exhibit nonlinear behavior and changing behavioral modes. For example, such a system may move from a condition of equilibrium, through a period of exponential growth, then proceed to exhibit oscillatory behavior. System Dynamics, unlike other modeling techniques, accommodates these nonlinear behavioral modes. It tracks the complex, dynamic relationships of system variables, demonstrating the trends of system levels over time. This, because of the subtlety and complexity of the interactions, is impossible to do over an extended period of time on an intuitive or mental basis. It should be noted that System Dynamics is not intended to do quantitative, point predictions of the future.

B. Basic Precepts of System Dynamics

The fundamental construct of System Dynamics is: *system structure determines the behavior of a system*. While other techniques explain events as caused by other events, or behavior as part of a time series, System Dynamics views events as part of behavior patterns that are themselves caused by the underlying system structure. Structure, in System Dynamics parlance, is defined as the system states and their interrelationships as determined by policy. Policy is defined as the rules that describe how available information is used to determine action.

Another primary construct of System Dynamics is: *the model of system structure is drawn largely from mental data*. Most of the world is run on the basis of mental information; here resides most of the knowledge about policy and the reasons for why things have happened in the past. By the time mental information is filtered down into the written record, much of the time-sensitive rationale for policy formulation is lost. The pressures that existed causing a particular decision to be made are not recorded. Furthermore, when written information is further condensed into numerical data, it loses the peripheral information that influenced the decision.

Consequently, the modeler should *determine the structure of the system by using the information that most of the decisions and policies are based upon, the mental information, rather than relying upon numerical data to infer structure* (Ref. 2). For this reason, managerial participation is imperative in the conceptualization phase of the DSN model development effort.

C. Elements of System Structure

Complex systems consist of multiple, interlocking feedback loops. A feedback loop is a closed path that connects (1) a system level (state) to (2) information about the level to (3) a decision that controls action concerning the level. Information is the observed or apparent level of the system and may not represent the true level.
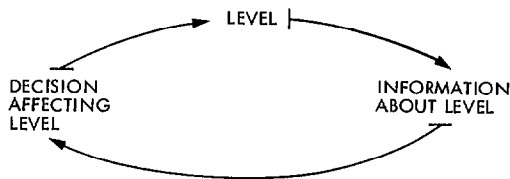
Feedback loops, the organizing principle of system structure, account for both the growth and stability of the system. Positive loops are goal divergent, moving exponentially from some point of equilibrium (thus accounting for growth or decay). Negative loops are goal seeking, or stabilizing structures. In a negative loop, any disparity between an apparent state and a desired goal generates inormation feedback that influences the system in a direction that reduces the discrepancy (Ref. 2).

It was previously stated that typically only 5 to 10% of those policies instituted to improve a given system are effective. This is because a great many of the attempted interventions get trapped in these negative, or compensatory, feedback loops. Here, a change applied to move the system in one direction produces a system change in the opposite direction.

The changing behavioral modes exhibited by a complex system may be accounted for by the nonlinear coupling of the various feedback loops within it. This condition can allow one loop to dominate the system for awhile, then cause control to shift to a loop elsewhere in the system. Thus, the same structure is producing behavior so different that it seems unrelated.

The System Dynamics modeling process involves transforming all elements of the real system into a feedback structure containing just two types of variables: levels and rates. Levels are the accumulations within the system — they describe the system state at any point in time. Rates are the system poli-

cies — the rules that determine what decisions are made affecting the levels. They reflect goals, observed conditions, the discrepancies between the two, and action.

Once the system structure is defined in these terms, a computer simulation technique (finite forward difference) is applied. The essence of this technique is, quite simply, that the value of a system level at time t is equivalent to its value at time $(t - 1)$ modified by the difference between the growth rate and the loss rate over the intervening time period.

The foregoing principles of System Dynamics are included in the model building methodology used for the development of the DSN Model. This methodology is described in the following section.

III. Methodology for Developing the DSN Models

Essentially, the process of building a System Dynamics model involves the same definition, design, construction, and testing/validation phases involved in building any good product. These phases form the generic classes from which the model builder will carry out the following specific activities:

(1) Definition Phase.

    (a) Identification of problem areas within the system.

    (b) Identification of questions that the model is to address.

    (c) Definition of the model boundary.

(2) Design Phase: development of the model feedback structure.

(3) Construction Phase: formulation of a computer program simulating the system structure.

(4) Testing/Validation Phase.

    (a) Performing simulation runs.

    (b) Testing and validation of the model structure.

    (c) Performing policy analysis and implementation.

Each activity is expanded in the following paragraphs.

A. Identification of Problem Areas

One cannot model a system without understanding its structure and recognizing its problem areas. Thus, the DSN Model builders will first investigate the DSN operational structure and dynamic behavior by talking to managers, and will then identify the problem areas with which managers are concerned. Identification of problem areas within a system

is not only the starting point for constructing a model, but also helps to achieve the purpose of the model: to solve system problems and enhance the effect of future policies.

B. Identification of Questions

Questions that managers would like answered are a major consideration during model construction. The ability of a model to process management queries and supply viable answers is a function that will drive the model design. Thus, the modeler must identify and focus on managers' questions as central points of the model concept (structure).

C. Definition of Model Boundaries

One of the preliminary activities involved in building a System Dynamics model is to identify the elements that are significant to the dynamic behavior of a system being modeled. These elements are included within the model boundaries. Thus, the DSN Model builders will define these elements prior to developing the model feedback structure.

D. Development of Model Feedback Structure

The preceding activities have been devoted to model definition. Having identified the organizational problem areas, obtained managers' questions, and defined the model boundaries, the model builders may then move forward to develop the feedback structure of the model. During this design phase, the modeler together with interested managers will formulate all the interrelationships that exist among the DSN elements. In so doing, the model feedback structure can represent the structure of the system (DSN) to be modeled. In addition, data collection activities should be performed prior to or during this phase.

E. Formulation of a Computer Program

Once the model feedback structure has been established, the computer program corresponding to the model structure can be developed. In so doing, the modeler will be able to interact with the model via a computer and perform further development and refinement activities.

F. Performing Simulation Runs

To investigate the behavior produced by a model, a number of simulation runs will be necessary. Simulation runs allow the modeler to exercise the model and see what system behavior it produces.

G. Testing and Validation of the Model Structure

The DSN Model structure will be drawn from managers' preceptions and intuitions regarding the DSN. Since mistakes can easily be made while linking these pieces of information

together, testing and validation of the model structure is a required activity.

Various techniques have been employed in System Dynamics modeling for the testing and validation of a model's structure and behavior. "There is no single test which serves to validate a System Dynamics model. Rather, confidence in a System Dynamics model accumulates gradually as the model passes more tests and as points of correspondence between the model and empirical reality are identified" (Ref. 4). Thus, a combination of tests will be employed for building confidence in the DSN Model. The tests fall into three categories: model structure tests, model behavior tests, and tests of policy implications of the model. The following subsections will discuss the concepts of these tests.

(1) *Tests of Model Structure:* Structure verification, parameter verification, and extreme condition are three widely used tests for examining the correctness of a model structure.

(a) Structure-Verification Test. This test examines whether the model structure coincides with that of the real system under study. One of the techniques that the DSN Model builder may employ to perform this test is to present the model structure to DSN managers. The managers will in turn comment as to the validity of the model structure based upon their perceptions of the real system.

(b) Parameter-Verification Test. When applying this test, the modeler will determine if the parameters incorporated within the model structure actually correspond to those perceived in the real system.

(c) Extreme-Condition Test. "Much knowledge about the real system relates to consequences of extreme conditions" (Ref. 5). For example, assuming that there is no food available for people (i.e., an extreme condition), one would expect the birth rate to approach zero. Structure in a System Dynamics model should, indeed, be able to demonstrate such extreme conditions since the model itself represents a real system. The DSN Model structure must be reexamined if extreme-condition tests are not met.

(2) *Tests of Model Behavior:* The process of comparing model-generated behavior to real-system behavior to evaluate the adequacy of a model structure is called the model behavior test. A series of model behavior tests may be employed to validate the DSN Model. They are: behavior reproduction, behavior prediction, surprise behavior, and behavior sensitivity.

(a) Behavior-Reproduction Tests. The behavior-reproduction tests are used to determine the model's

ability to replicate behavior observed within the real system. Behavior-reproduction tests include: symptom generation, frequency generation, relative phasing, multiple mode, and behavior characteristics. These tests serve the common purpose of examining whether or not a model recreates the symptoms of problems that were observed in the real system.

(b) Behavior-Prediction Tests. "Behavior-prediction tests are analogous to behavior-reproduction tests. Whereas behavior-reproduction tests focus on reproducing historical behavior, behavior-prediction tests focus on future behavior" (Ref. 6). In other words, behavior-prediction tests are used to examine whether a model will generate patterns that are expected to happen in the future.

(c) Surprise-Behavior Test. A more comprehensive model may well display behavior that exists within the system but has not been previously recognized. When such a situation occurs, the modeler must investigate the causes of the unexpected behavior within the model and determine if such characteristics are exhibited within the real system. By thus employing the surprise-behavior test, the DSN Model builder can investigate the model with respect to its full usefulness.

(d) Behavior-Sensitivity Test. This test is used to ₁examine how changed parameter values within the model will affect the model's behavior. One will establish more confidence in the model structure if its generated behavior, resulting from the parameter changes, corresponds to that perceived in the real system.

(3) *Tests of Policy Implications.* Policy implication tests are used when one wishes to check the model's predictive ability with respect to policy analysis. There are two major difficulties in using the results of policy tests. First, when implementing a new policy (found beneficial from exercising the model), a fair amount of time is required to ascertain the results. It is time consuming. Second, implementing a new policy that has been recommended by the model can be risky.

The changed behavior-prediction test (one of the policy tests) can be used to circumvent the difficulties discussed above. Thus, this test (discussed in the following paragraph) will be employed to examine the usefulness of the DSN Model as a policy analysis tool.

"The changed-behavior prediction test asks if a model correctly predicts how behavior of the system will change if a governing policy is changed. The test can be made by examining responses of a model to policies which have been made in the real system to see if the model responds to a policy change as the real system responded" (Ref. 7). Therefore, by employing this test, the risks that may occur when performing the other policy tests can be avoided.

H. Performing Policy Analysis and Implementation

Once the DSN Model has been built, and confidence in its structure and behavior have been established through various tests, it can then be utilized as a policy analysis tool. The system structure, represented in the model, includes the existing organizational policies. Thus, one can simulate changes in policy by judiciously tweaking the relevant parts of the model structure and observing the effects. New policies may be evaluated and if desirable results are obtained, these new policies may be implemented in the real system. For example, policy analysis may be performed to determine the most effective allocation of limited resources. During this activity, the modeler will demonstrate policy analysis to the manager by exercising and interacting with the model.

I. Sustaining

Future modifications to the model will be required and are desirable so as to maintain a model structure that corresponds to the dynamic nature of the real system. Therefore, once the DSN Model is completed, some sustaining activity will be necessary.

Figure 1 illustrates and summarizes the methodology explained above that will be used for the development of the DSN Model.

IV. Progress to Date

A System Dynamics model of the DSN, called DSNMOD, was built in the early seventies. The first step, in the process of developing DM then, was to analyze and describe the existing model. This was done and the following conclusions were drawn. The older model is a thorough representation of the DSN from one person's perspective. The base of understanding built into such a model, however, must be broadened. Secondly, the model addresses itself to the structure of the DSN in the sixties and very early seventies. The DSN structure has been modified since that time, and the newer structure must be represented. Lastly, the model, as a tool for managers, must be widely discussed by current managers and must be directed toward today's planning questions. These conclusions were integrated into the implementation plan for the DSN Model.

The team working on the DM task next interviewed over 20 TDA and DSN managers to ascertain the uses and questions to which DM should be applied. Three products came from these interviews: (1) a list of questions that managers would like to see addressed by the model, (2) a conceptual model of what the DSN strategic planning structure is, and (3) the functional requirements for DM. The functional requirements were reviewed by a board of TDA and DSN managers, plus an expert in the field of System Dynamics.

To further support the development efforts, the task team received training in System Dynamics, analyzed other useful modeling techniques, performed preliminary analysis of data needs and availability, and made presentations to TDA and DSN personnel on the task and the technique. Most recently, a computerized demonstration model of the DSN, using System Dynamics, was developed, coded, run, analyzed, and presented.
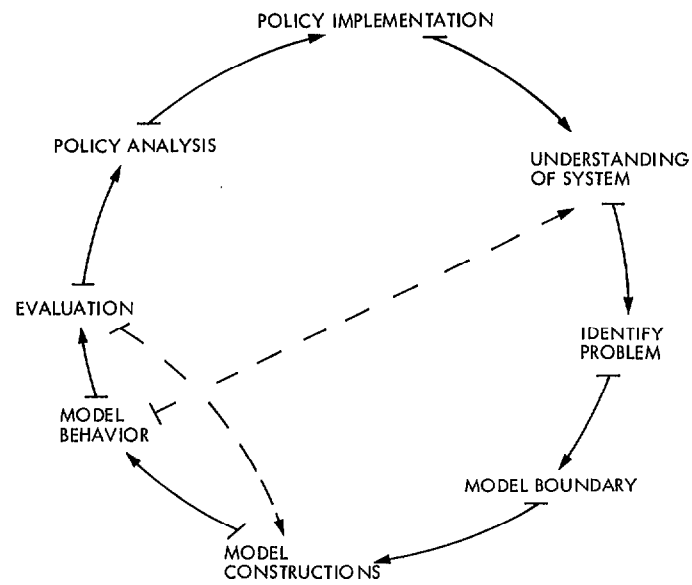
V. Future Work

Questions that concern DSN managers involved in strategic planning seem to fall into the formats given in Section I. However, each manager has a different perspective and a different segment of the DSN with which he/she must be concerned. Thus, the number of potential strategic planning questions that DM could address is quite large. An important step in the development of DM, then, is choosing a few questions for DM to address in its initial form. The remaining questions can be addressed as refinements or extensions to the base model.

The full methodology (discussed in Section III) will be employed to develop the base model for DM. This base model is expected to be available by January 1982. Subsequently, the high level design for all of DM will be written and reviewed, further extensions of the model will be developed, reviewed, and documented, and the complete DM set will be transferred to a sustaining state in the fall of 1983.

References

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3. Forrester, J. W., *Industrial Dynamics*, M.I.T. Press, Cambridge, Massachusetts, 1961, pp. 107-114.

4. Forrester, J. W. and Senge, P. M., *Tests for Building Confidence in System Dynamics Models*, Alfred P. Sloan School of Management, Massachusetts Institute of Technology, December 16, 1978, p. 2.

5. Ibid., p. 8.

6. Ibid., p. 15.

7. Ibid., p. 23.

Fig. 1. Methodology for developing the DSN Models (from Ref. 2)

POLICY IMPLEMENTATION

POLICY ANALYSIS

UNDERSTANDING
OF SYSTEM

EVALUATION

IDENTIFY
PROBLEM

MODEL
BEHAVIOR

MODEL BOUNDARY

MODEL
CONSTRUCTIONS